The Minos Experiment

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- Overview
- NUMI Beam
- Minos Detectors
- Physics Capabilities
- First (non-beam) Data

The MINOS Collaboration

175 physicists from 31 institutes in 5 countries

U.K.

Russia

U.S.A.

Greece

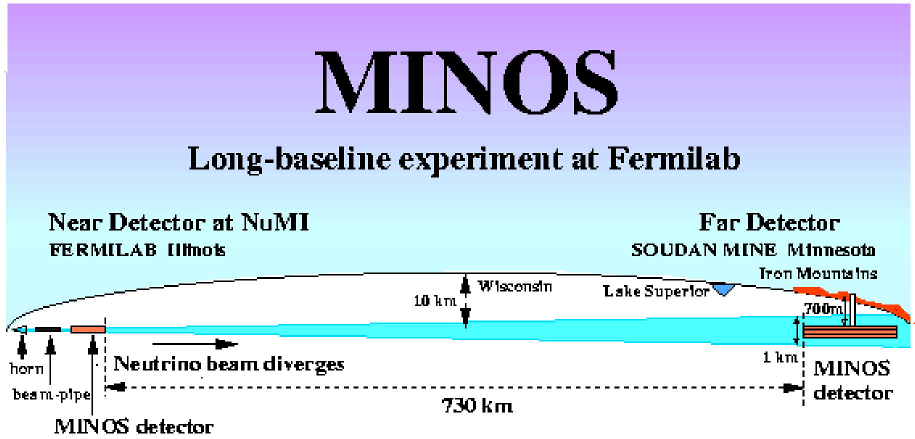
France

Brazil

Argonne – Athens – Brookhaven – Caltech – Cambridge – Campinas – Fermilab – College de France – Harvard – IIT – Indiana – ITEP Moscow – Lebedev – Livermore – Minnesota, Twin Cities – Minnesota, Duluth – Oxford – Pittsburgh – Protvino – Rutherford Appleton – Sao Paulo – South Carolina – Stanford – Sussex – Texas A&M – Texas-Austin – Tufts – UCL – Western Washington – William & Mary - Wisconsin

Minos collaboration members at Fermilab with the Near Detector surface building in the background (right)

MINOS : Overview

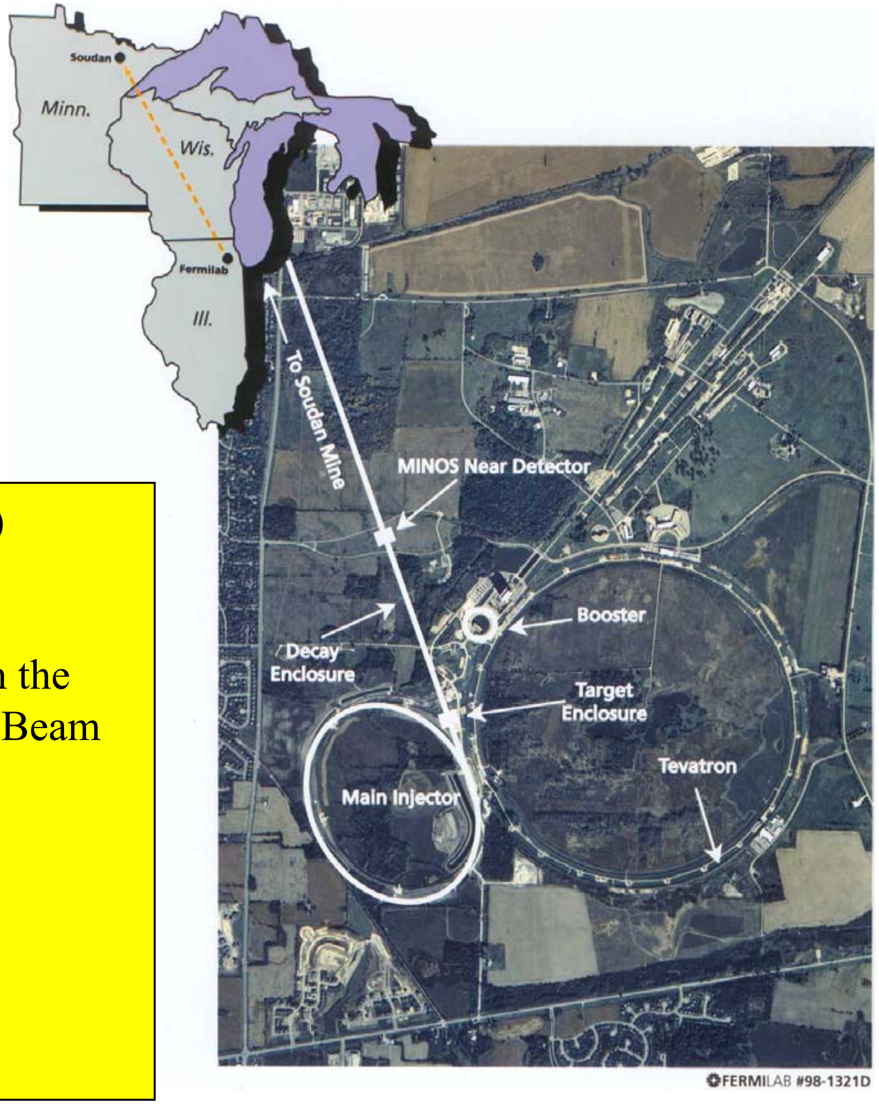


High intensity ν_μ beam from Fermilab to Soudan (Mn)

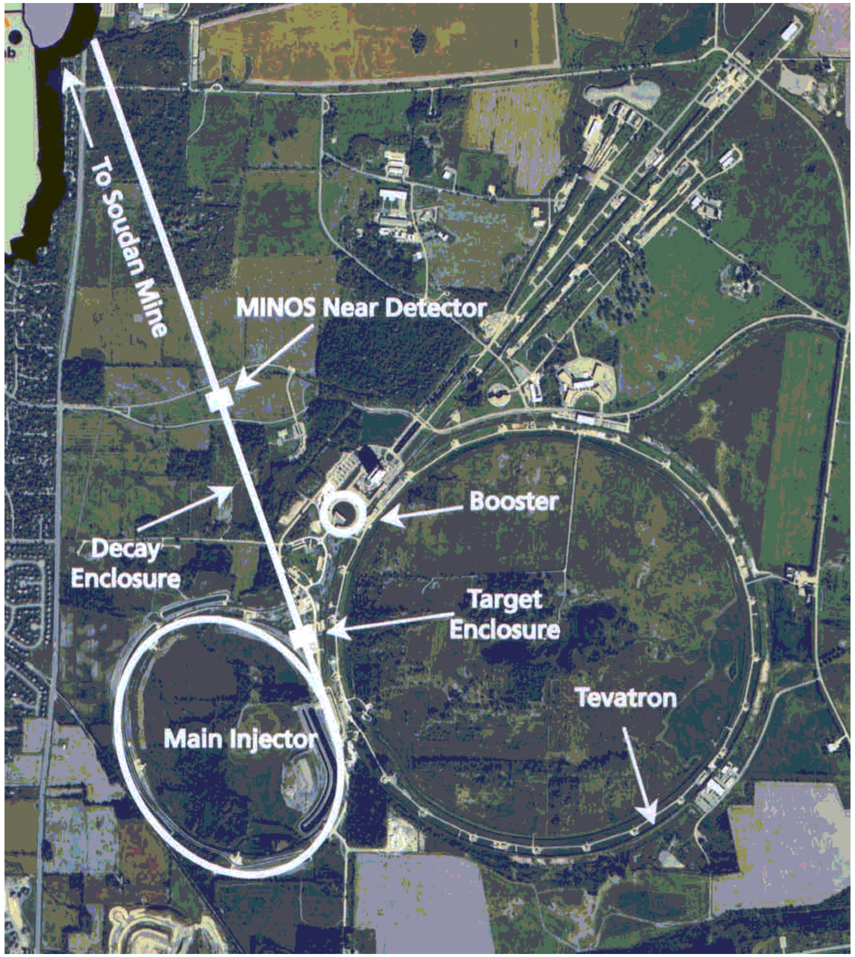
Two detectors, Near (1kT) and Far (5.4kT)

Primary measurement : Compare ν energy spectrum in the Far Detector to the un-oscillated expectation from the Beam and Near Detector

- Observe oscillation minimum
- Confirm oscillatory behaviour in ν_μ sector
- Measure Δm_{23}^2 to ~10%
- Look for evidence of $\nu_\mu \to \nu_e$ oscillations



NUMI Beam - Features

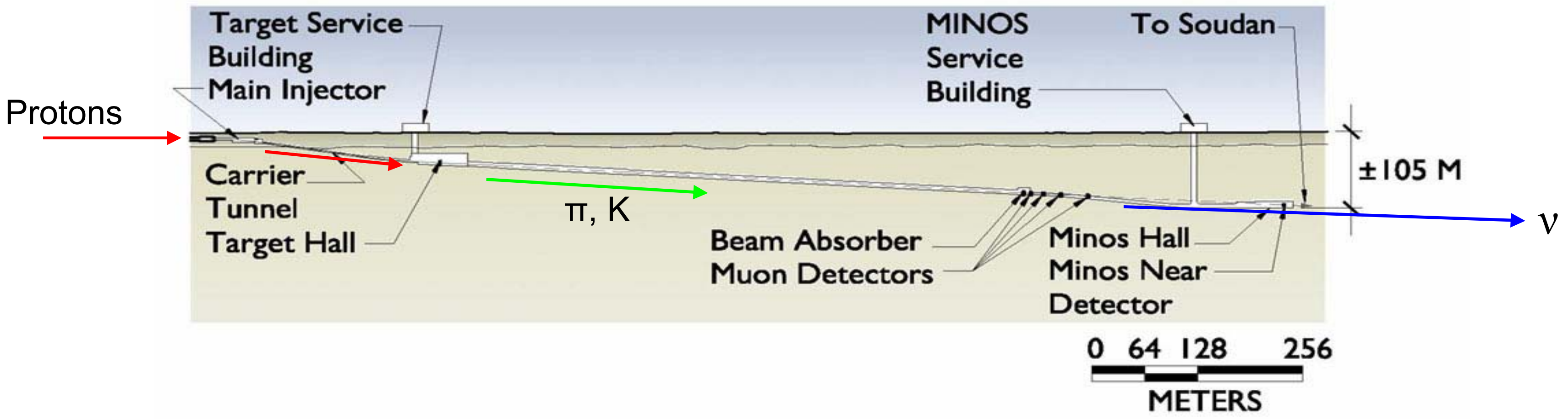


Primary Features

- 120 Gev protons extracted from main injector
- STE - 8.67 μs spill, 1.9s repetition rate
- New ν beam line built - intense beam
  - 2.5 10^{13} protons/spill
  - 300kW primary proton beam

  } At startup
- Neutrino energy tuneable
- Initial intensity 2.5 10^{20} protons/year

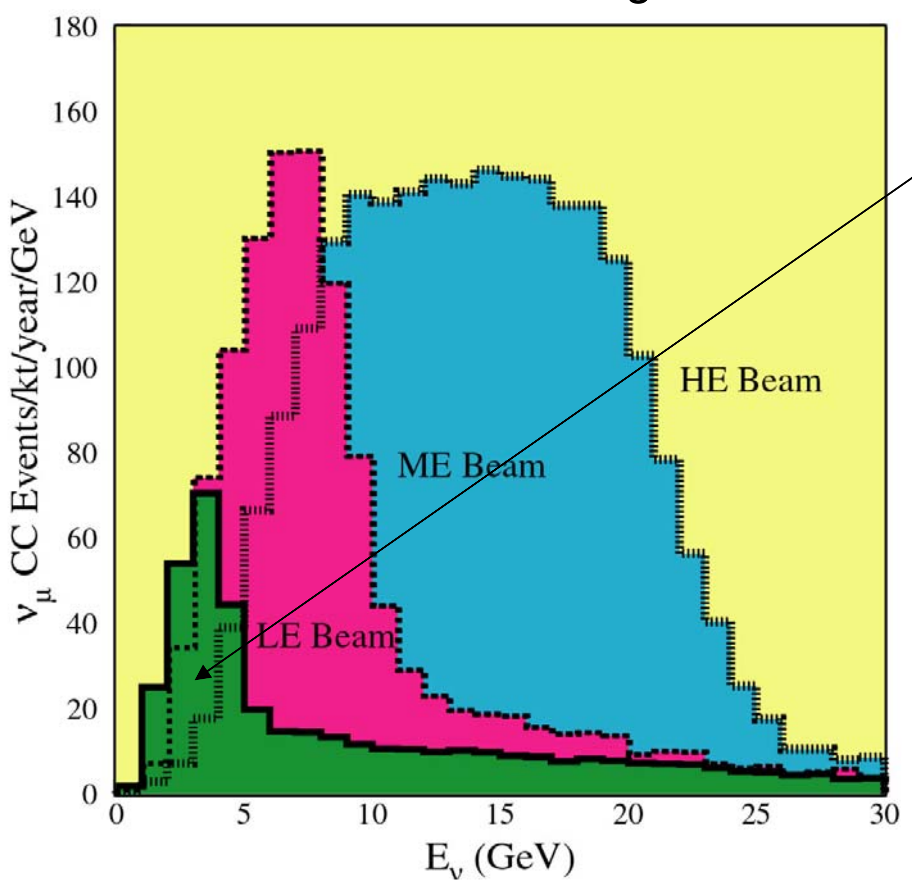
NUMI Beam



- 120 GeV protons extracted from MI into NUMI beam tunnel
- Bend downwards (3.3° downward bend) – beam must point at Soudan
- Incident on graphite target
- Focus charged mesons (π, K) with two magnetic horns pulsed with 200kA
- 675m long steel decay pipe for pions to decay (1.5 Torr, encased in 2-3m concrete)
- Hadron absorber downstream of decay pipe
- 200m rock in front of Near Detector for muon absorption
- Beam energy tuned by moving 2nd horn relative to target. Polarity selects ν, anti-ν

NUMI Beam - Configurations

Nominal Beam Configurations



Beam energy can be tuned by adjusting position of 2nd horn relative to target

LE beam best match for $\Delta m^2 \sim 2\text{-}3\ 10^{-3}\ eV^2$

Both ν_μ and $\overline{\nu_\mu}$ beams - $\overline{\nu_\mu}$ later running

First beam will be in December 2004

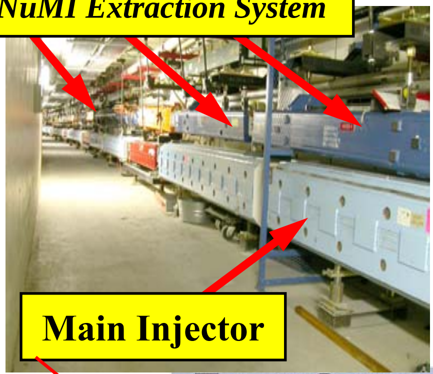
Beam turns on with 2.5 10^{20} protons/year

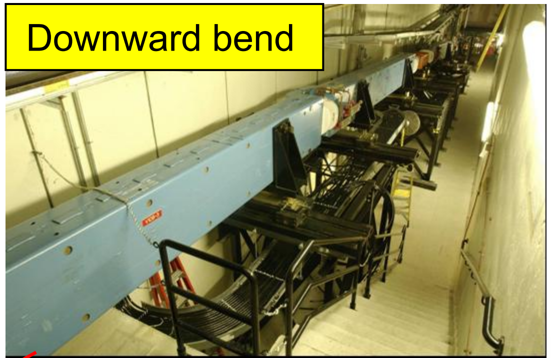
Studies in progress to improve on this

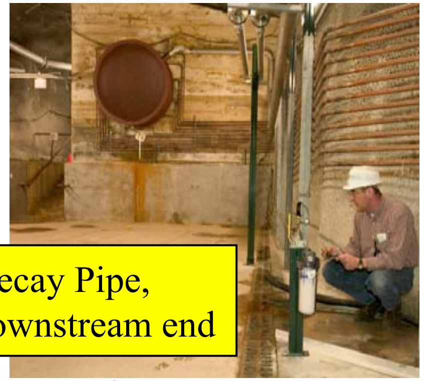
ν_μ CC Events/year
(with no oscillations)

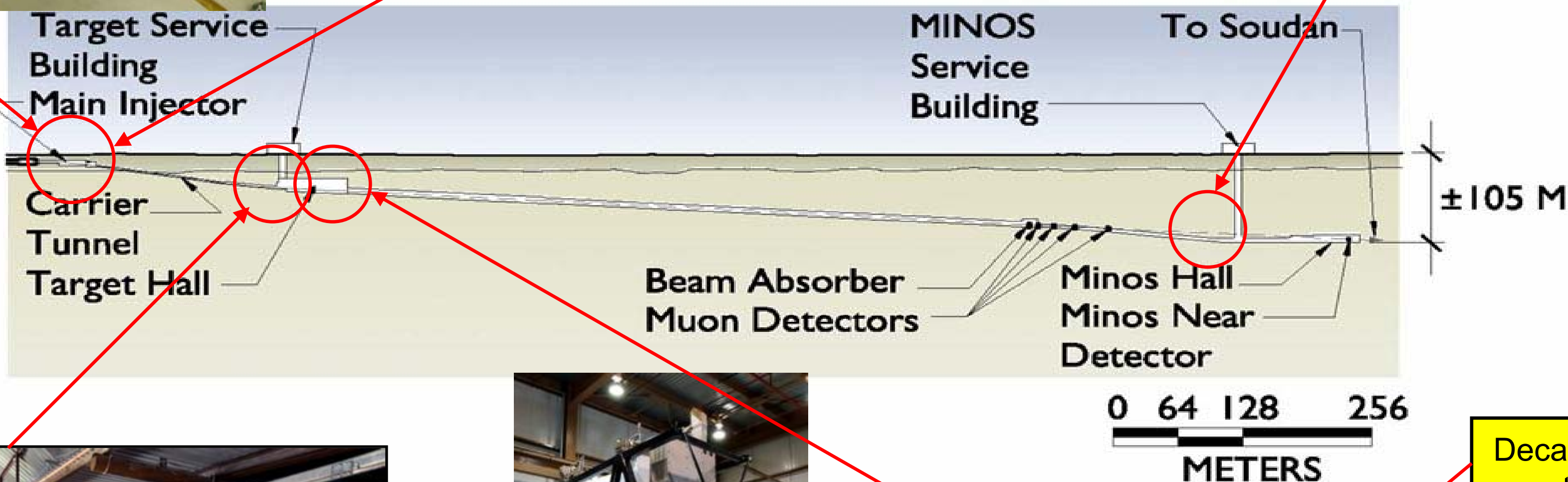
Low	Medium	High
1,600	4300	9250

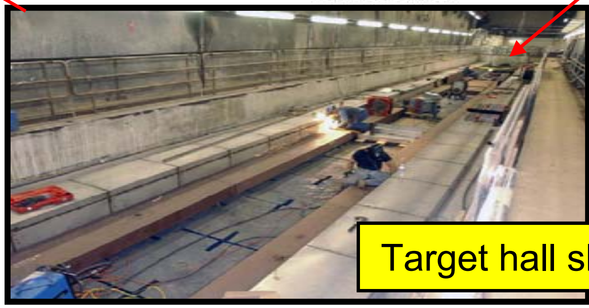
NUMI Beam - *Status*











MINOS Far Detector

Site: Soudan Mine, Minnesota, 735 km baseline

New cavern excavated for MINOS

Depth 2341ft = 2070 mwe

'Traditional' access methods!

The detector all went down this shaft

MINOS Far Detector

The completed Minos Far Detector

Data taking since ~ September 2001
Installation fully completed in July 2003.
Atmospheric ν / cosmic μ data sample

5.4 kton <u>magnetised</u> tracking calorimeter, B ~1.5T

484 steel/scintillator planes built in 2 supermodules

2.54cm thick steel, 192 4x1cm scint. strips per plane

- orthogonal orientation on alternate planes – U,V
- optical fibre *readout*

Veto shield covers top/sides for atmospheric ν

Multi-pixel (M16) PMTs read out with VA electronics

- 8-fold optical multiplexing
- chips individually digitised, sparsified & read out when dynode above a threshold
- excellent time resolution – 1.56ns timestamps

Continuous *untriggered* readout of whole detector

Interspersed light injection (LI) for calibration

Software triggering in DAQ PCs (independent of ND)

- highly flexible : plane, energy, LI triggers in use
- spill times from FNAL to FD trigger farm under dev.

GPS time-stamping to synch FD data to ND/Beam

MINOS Near Detector

Site: Fermilab, ~ 1 km

Minos Near Detector as installation neared completion

Plane installation fully completed on Aug 11, 2004

1 kton (total mass) magnetised tracking calorimeter

Same basic design as Far Detector

Partially instrumented

- 282 steel planes, 153 scintillator planes
- reduced sampling in rear planes (121-281) "spectrometer section" used for muon tracking

High *instantaneous* ν rate, ~ 20ev/spill in LE beam

No multiplexing except in *spectrometer* region (4x)

Fast "QIE" electronics

- continuous digitisation on all channels during spill (19ns time-slicing). Mode enabled by spill signal.
- dynode triggered digitisation out of spill (cosmics)

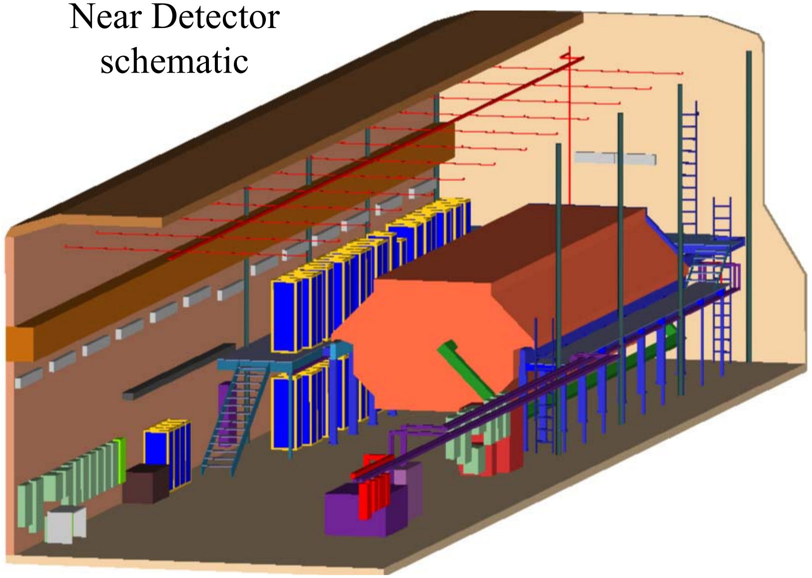
GPS time-stamping / Software triggering in DAQ

- all in spill hits written out by DAQ
- standard cosmics triggers out of spill

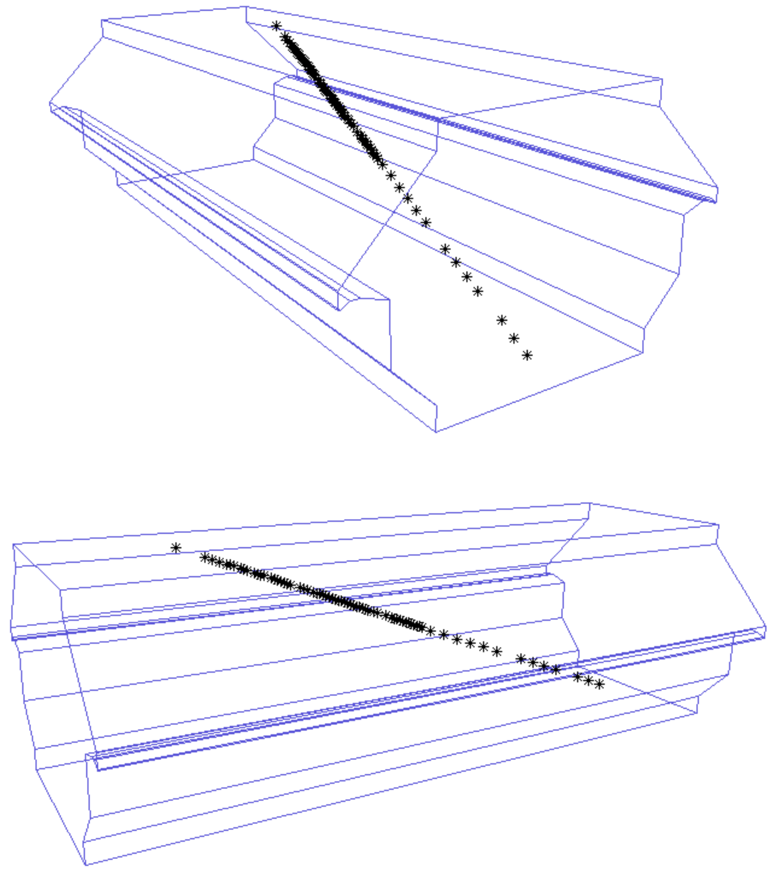
Near Detector

Cosmic rays triggered and readout

Near Detector
schematic



3D view of cosmic μ read-out from the Near Detector



Installation nearing completion

Detector working!

Coil installed over coming weeks

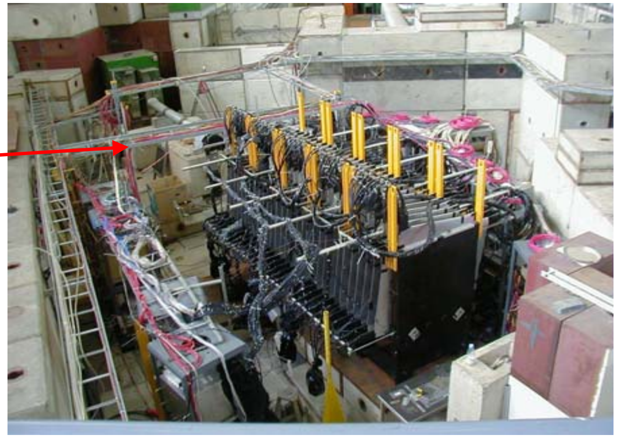
Calibration Detector

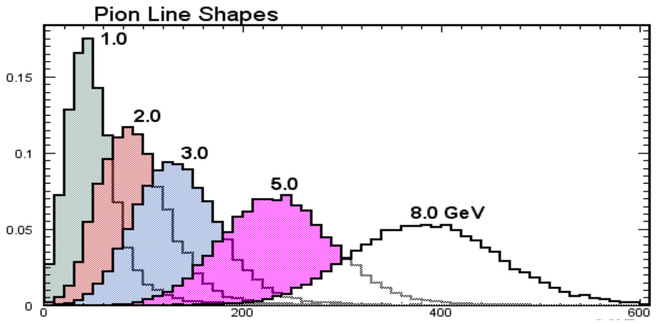
The 3rd major Minos detector

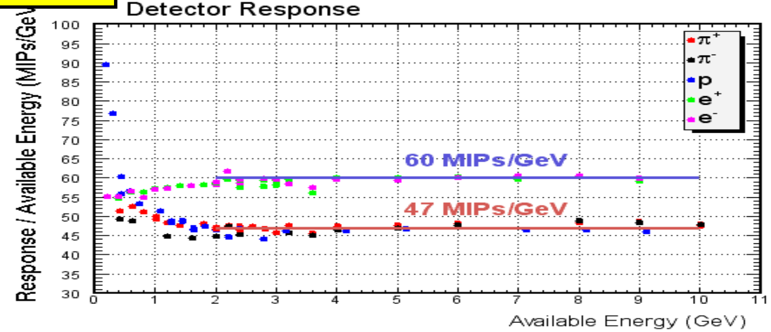
- Vital to understand energy response to reconstruct E_ν

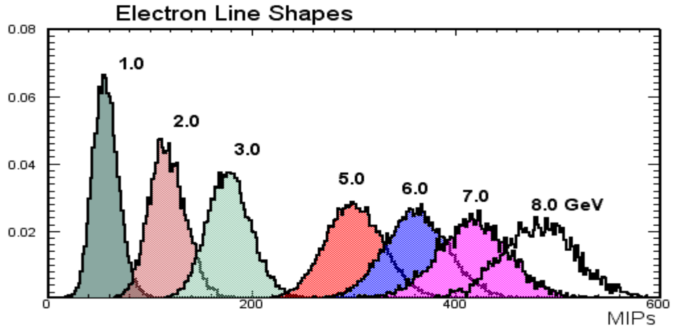
$$E_\nu = p_\mu + E_{had}$$

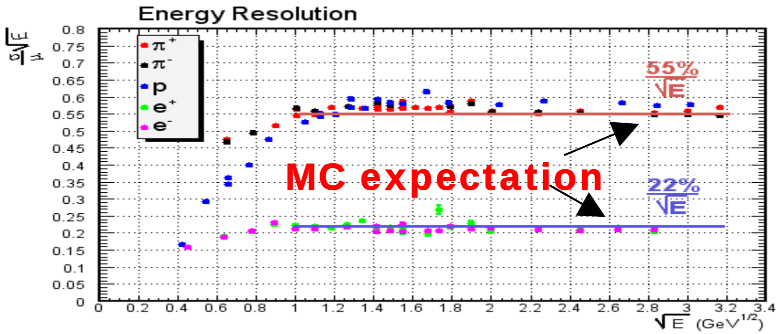
- Measured in a CERN test beam with a "mini-Minos"
  - operated in both Near and Far configurations
  - Study e/μ/hadron response of detector
  - Test MC simulation of low energy interactions
  - Provides calibration information







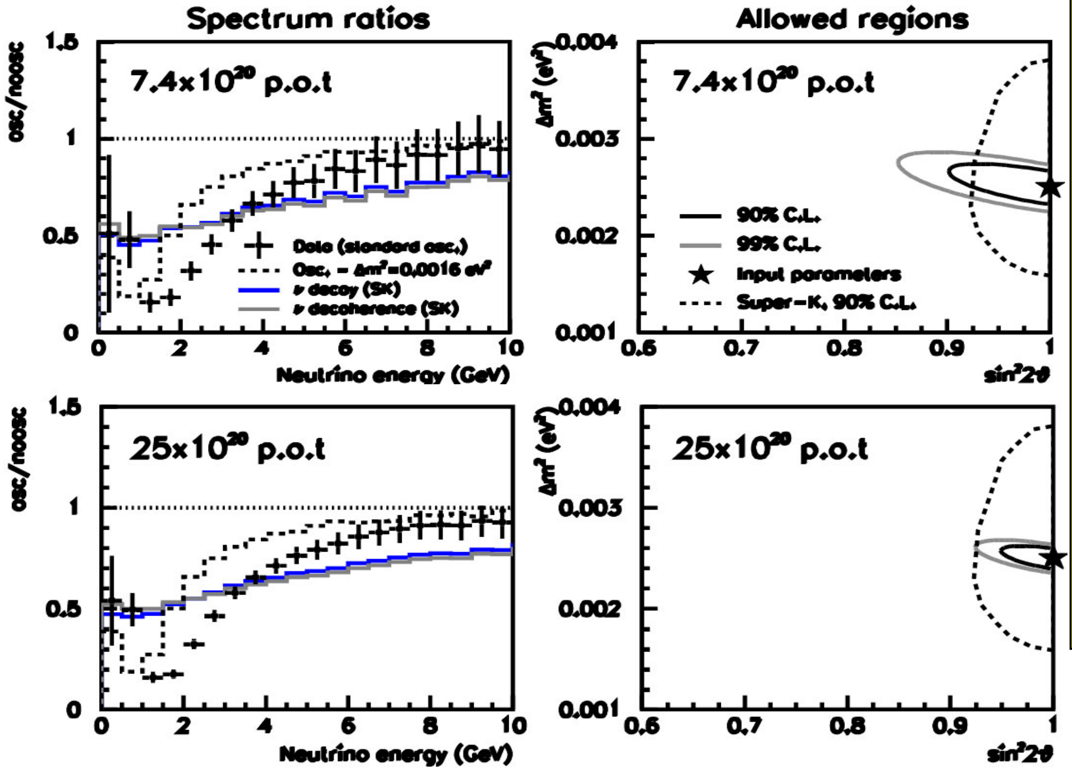




MINOS Sensitivity

Sensitivity for two exposures

($\Delta m^2 = 2.5\ 10^{-3} eV^2$, $\sin^2 2\theta = 1.0$)



ν_μ **CC** events

Reconstruct ν_μ energy

$$\mathbf{E_\nu = p_\mu + E_{had}}$$

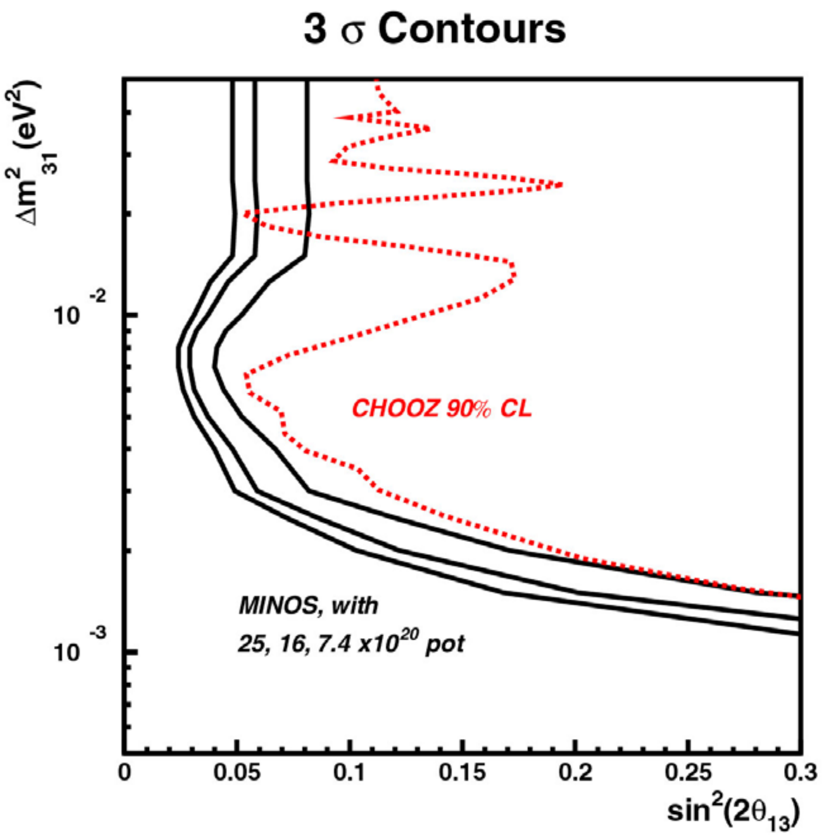
Compare observed energy spectrum at Far Detector with un-oscillated expectation from Near Detector and Beam.

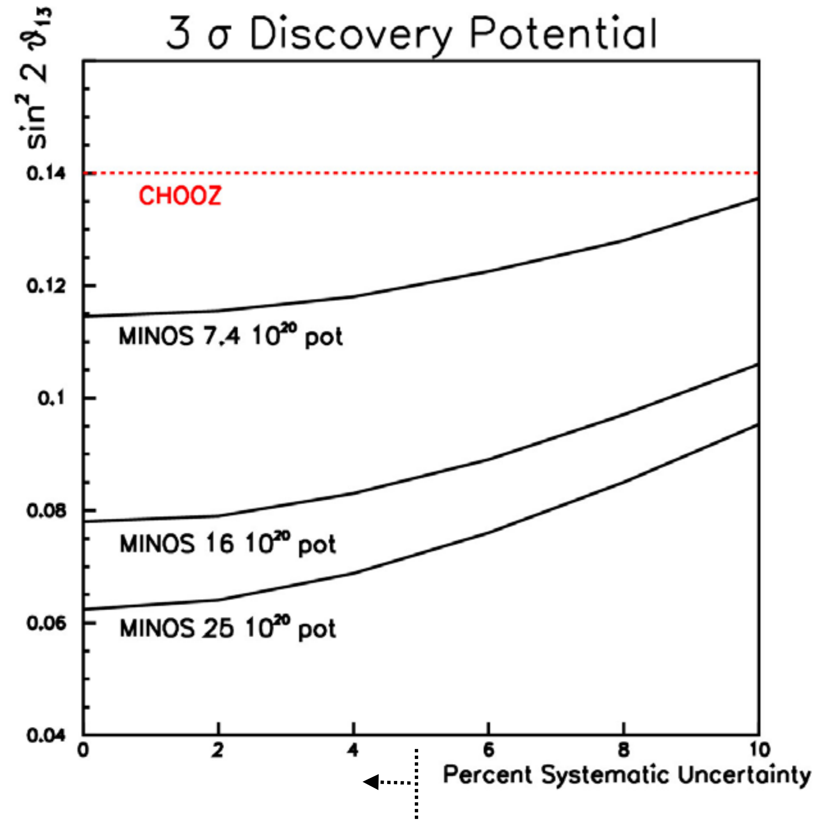
Direct measurement of L/E dependence

Observe oscillation minimum

$\sin^2 2\theta$, Δm^2 measurement from depth and position of oscillation minimum

ν_e appearance





Can improve on CHOOZ limit

Chance of measuring θ_{13} !

Reach is much improved with more protons

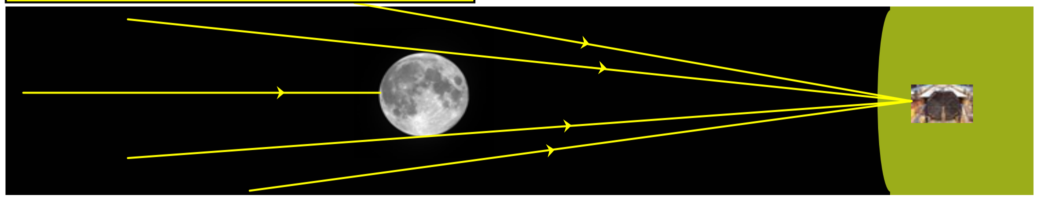
We have Far Detector data

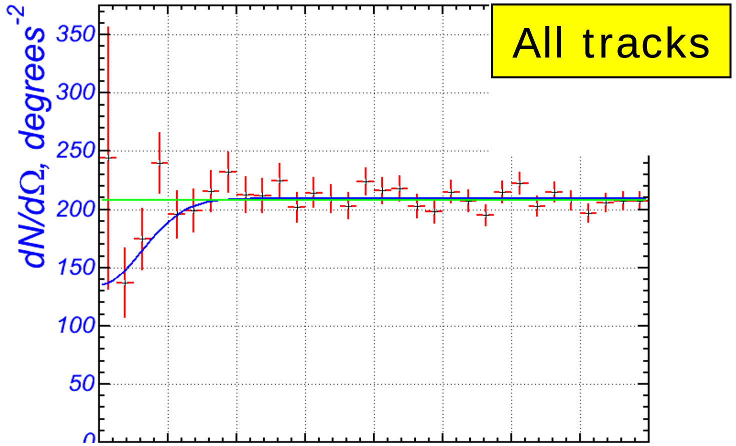
Cosmic muon & atmospheric analyses

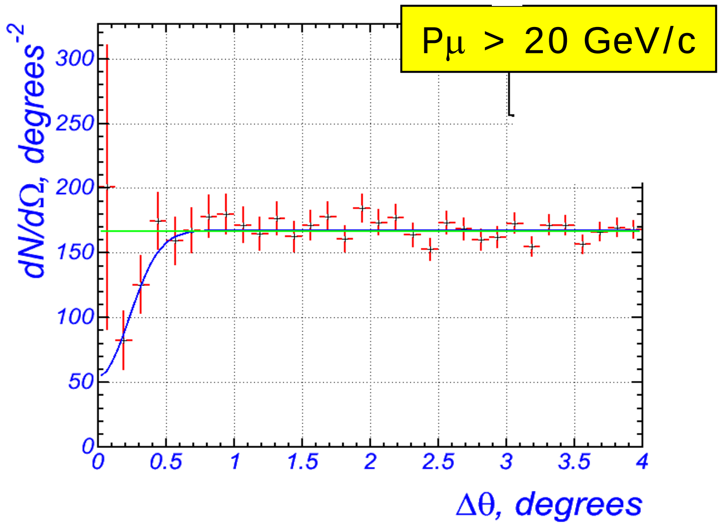
Far Detector Data

Moon Shadow

HE primary cosmic rays shadowed by moon







Sample of 10M muons analysed

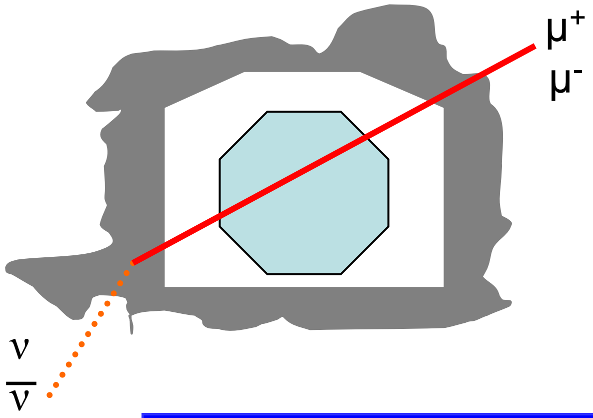
Observed shadow of the moon

Angular resolution improved by selecting high momentum muons

Clear moon shadow – good resolution

Far Detector Data

Upward going muons



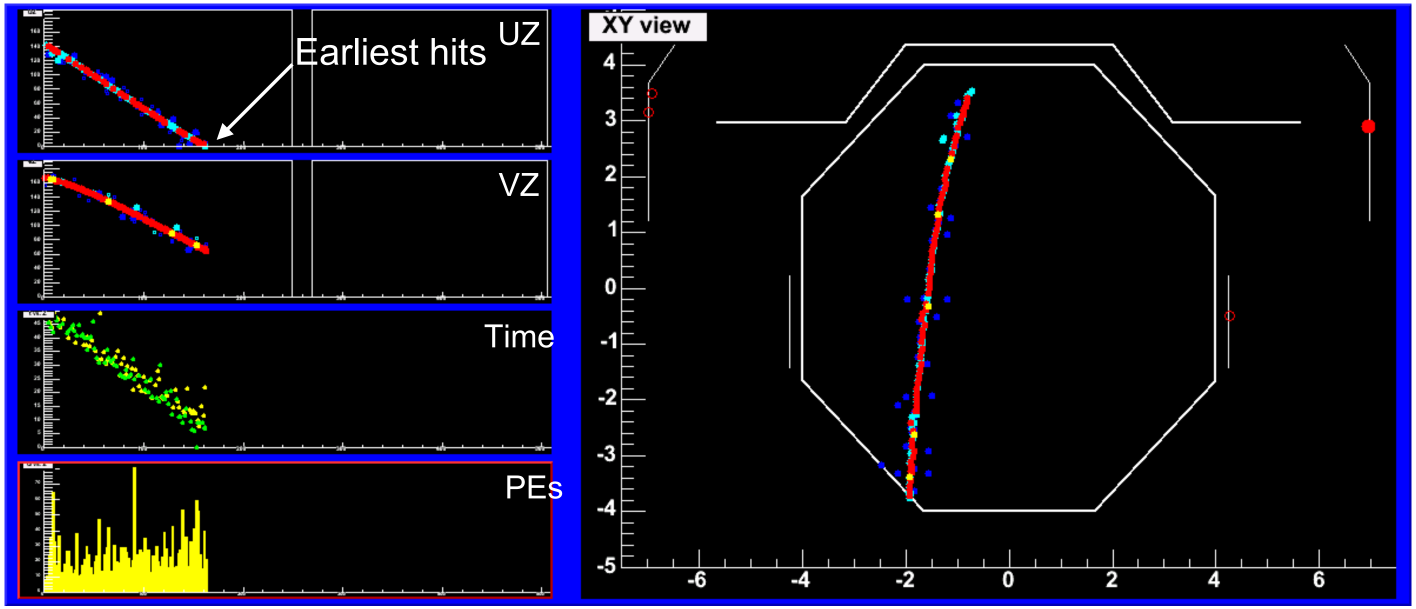
Neutrinos interact in rock surrounding detector

Upward going muons ~ 0 background

Identified on basis of timing

- electronics provides 1.56ns timestamps

Expect : 1 event / 6 days



Far Detector Data

Upward going muons

Selection

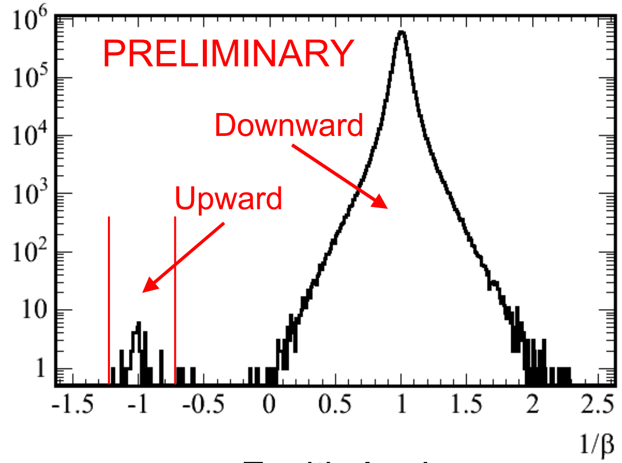
Require clear up/down resolution from timing

- 'Good track', > 2m long, > 20 planes

Calculate μ velocity from hit times, $\beta = v/c$

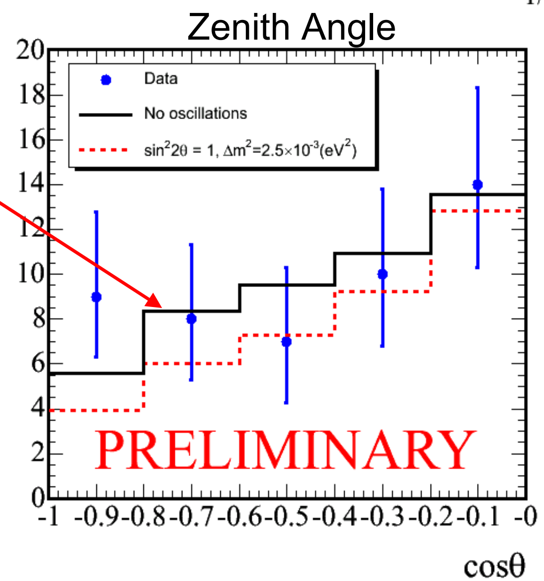
Good separation of up/down going μ ($\sigma_{1/\beta} \sim 0.05$)

48 upward events



Zenith angle distribution compared with MC

MC : NUANCE with Bartol '96 flux. Normalized to data



Charge Tagging using muon charge

	ν	$\bar{\nu}$	$\nu, \bar{\nu}$?
Events	13	8	27

Understanding systematics : Work in progress

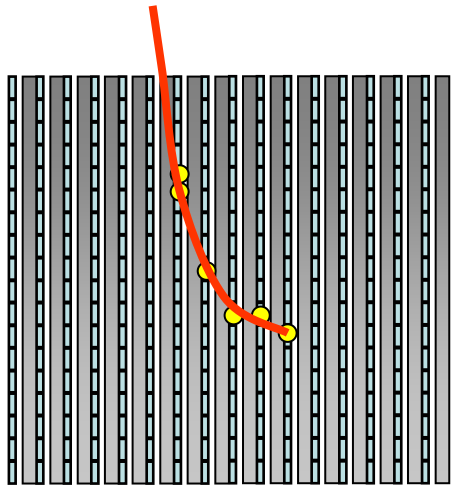
Far Detector Data

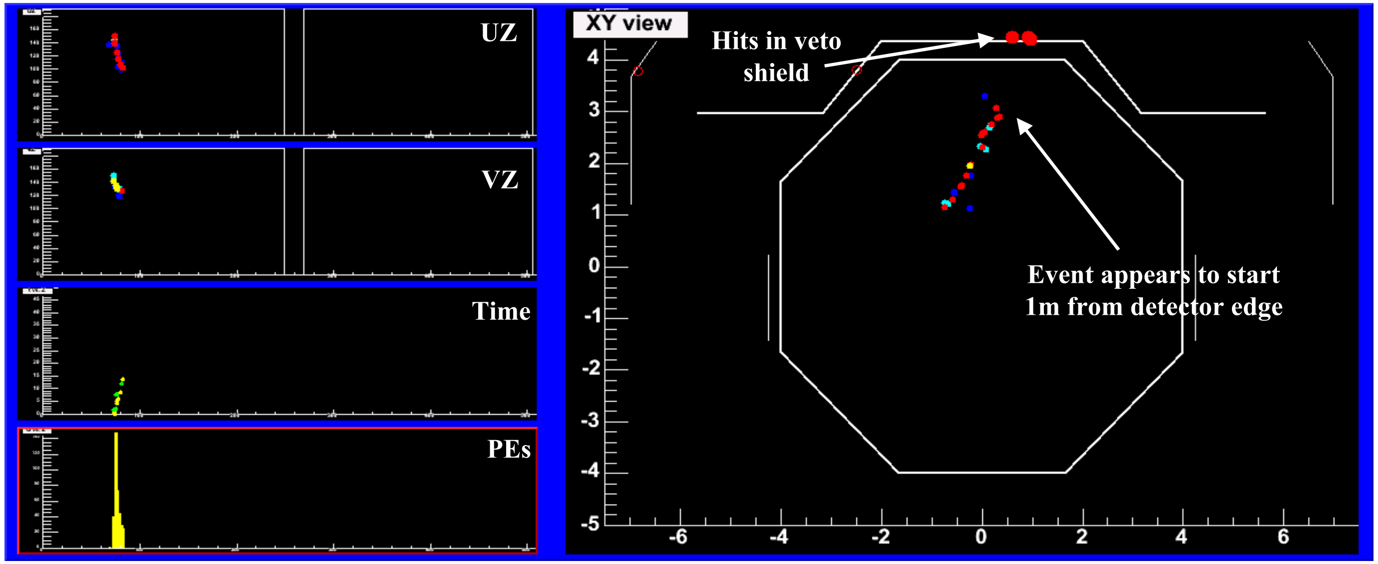
Atmospheric Neutrinos

Minos designed for νs from Fermilab, not from 4π

Planar detector – Vertical gaps – Potential problem for atmospheric νs

For contained events, the veto shield significantly reduces background from cosmics entering detector through gap between planes





Signal to noise ~ 5 10^{-6}

Veto shield helps

Far Detector Data

Atmospheric Neutrinos – Event Selection

Selection

- Fiducial Volume: little activity within 50cm of detector edge
- Reconstructed muon track – track crossing 8 planes
- Cosmic muon rejection – remove steep events
- Veto shield – no *in-time* veto shield hit

95% purity

75% efficiency

Event Statistics (1.87 kton-years)

MINOS PRELIMINARY	DATA	MC no osc**	MC Cosmic bg.
Before VETO	88	39	63 ± 6
VETOED	51	2	61 ± 6
Selected	37	38 ± 8	2

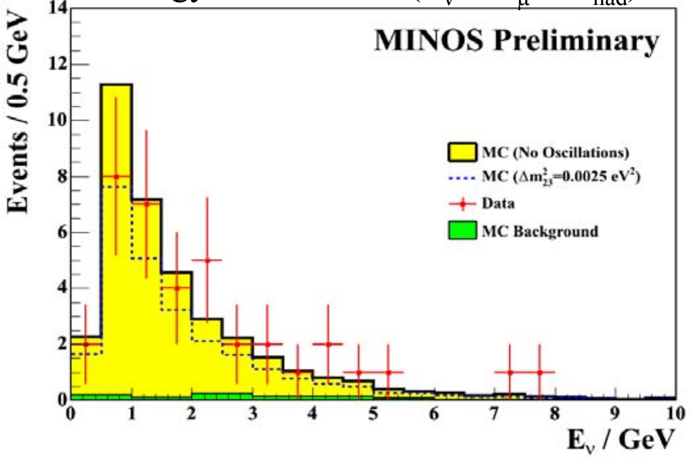
** Does not include acceptance systematic uncertainties

Vetoed background agrees with MC expectation

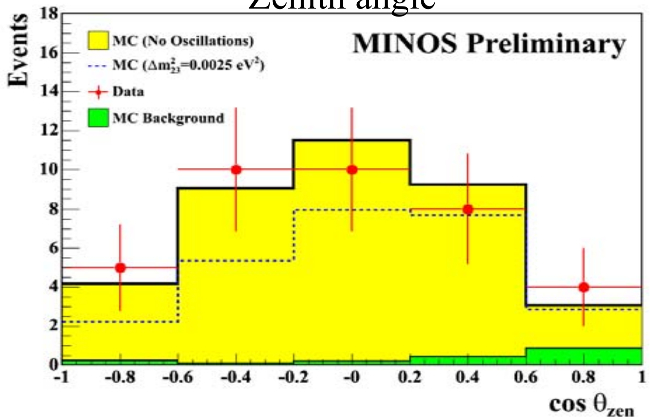
Far Detector Data

Atmospheric Neutrinos – Preliminary Data

Energy distribution ($E_\nu = E_\mu + E_{had}$)

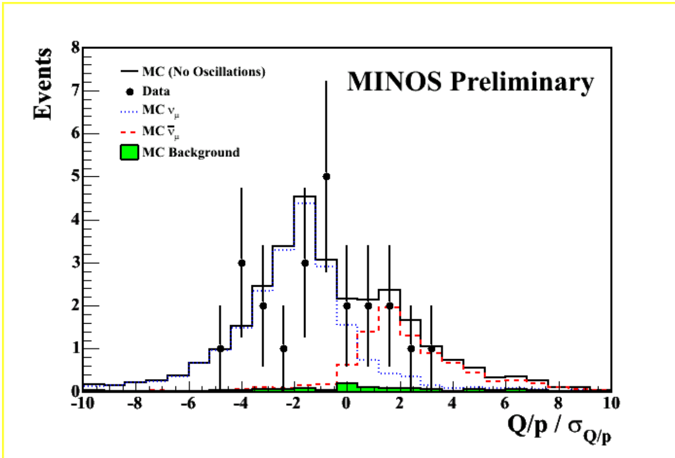


Zenith angle



- MC normalised to the data (no oscillations)
- Cosmic background from data is from number of vetoed events
- Statistics are still low – but exposure steadily increasing!
- More data needed

Charge separation using muon curvature



6 $\bar{\nu}$

17 ν

14 no ID

$N_{\bar{\nu}}/N_\nu = 0.35 \pm 0.17$

Conclusions

- NUMI beam installation well advanced and on schedule
- Minos Near Detector nearing completion
  - Final plane of detector installed Aug 11, 2004!
- Minos Far Detector fully operational
  - Data taking since first planes installed, August 2001
  - Routine physics quality data taking since mid 2003
  - Cosmic ray / atmospheric neutrino studies under way
  - First direct observation of separated atmospheric neutrinos
- MINOS in good shape
  - Protons on target in December 2004
  - First beam physics runs early 2005